NE Syrtis	Location (lat,lon):	18N, 77E

Summary of observations and interpreted history, including unknowns:

The landing site is located within the rings of the Early/Middle Noachian Isidis impact basin that excavated and exposed Fe/Mg-clay and pyroxene-rich crust forming a basement unit. Basement texture is largely smooth and massive (at scales visible from orbit) with large mounds of pyroxene-enriched subunits. The well-exposed clay basement unit is interspersed with lithified ridges (possibly from hydrothermal flow) exposed by erosion. Diverse megabreccia throughout the basement (some blocks >100m in diameter), include layered (possibly pre-Isidis Pre-Noachian/Early Noachian sedimentary) Fe/Mg clay minerals and primary igneous (pyroxene-rich) blocks. Shortly after the impact, olivine-enriched materials were emplaced unconformably as impact melt sheet cumulates or low viscosity picritic lavas. This is now exposed in meters-high steep-sided mesas several hundreds of meters in size. The banded or layered olivine unit is well-exposed, polygonally fractured at meters-scale, and extensively altered to Mg-carbonates. The three main hypotheses for carbonate formation are as part of a serpentine springs system (serpentine is positively detected in the same unit ~25km away), formation from an aquifer hosted within the olivine-enriched unit, or formation from extensive interaction with surface waters. The olivine unit contacts with the basement and overlying mafic cap are well-exposed throughout the region. This stratigraphy was cut by the Nili Fossae graben, prior to the emplacement of the Syrtis Major volcanics. Some portions of the basement in the ellipse have an upper kaolinite or kaolinite-jarosite layer overlying, perhaps from near-surface alteration. The entire section is capped by a high-Ca pyroxene mafic unit with low thermal inertia, possibly related to the Syrtis Major volcanics. Further to the south, an extended mission target above the olivine unit is a 500-m thick sequence of sedimentary sulfate deposits, capped by lava flows from the Early Hesperian Syrtis Major formation. Subsequent to the Syrtis volcanic flows, a period of gradation by surface waters created fluvial channels in the volcanics as well as the basement. There is good evidence that fluvial activity preceded, was concurrent with, and continued after the global period of valley network and open basin lake formation. The NE Syrtis region has well-defined aqueous and igneous units exposed evenly throughout the landing ellipse. The exposures span >=400 Myr and include 4 water-related habitable environments and 3 igneous units. The region also has two well-established stratigraphic endpoints: (1) the Isidis Basin forming event (2) emplacement of Syrtis Major lavas.

Summary of key investigations

-Determine the origin of the carbonate and its preserved isotopic record of the atmosphere ($\delta^{13}C$ records loss); if related to serpentinization, determine the temperature and redox based on mineral assemblages
-Establish the composition, nature, and origin of the Noachian clay rich basement
-Interrogate the origin of Al phyllosilicates, thought by some to be weathering zones indicating clement temperatures and by others to be zones of acid-leaching
-Search for biosignatures in the 4 water-related units (layered PreN megabreccia, clay basement, carbonates, Al clay weathering zones).
-Perform a stratigraphic cross section, sampling of key igneous and aqueous units spanning the Early Noachian to Early Hesperian, including datable units, to understand major transitions in Mars history
-Sample Early (or Pre) Noachian units preserved in the breccia blocks; test for magnetism/age in rtn samples to constrain dynamo

Cognizant Individuals/Advocates:

J. Mustard, B. Ehlmann, D. Des Marais, J. Head, M. Bramble, D. Quinn, et al.

Link to JMARS session file | Link to Workshop 2 rubric summary

<insert link here> | <insert link here>

Key Publications list (grouped by topic):

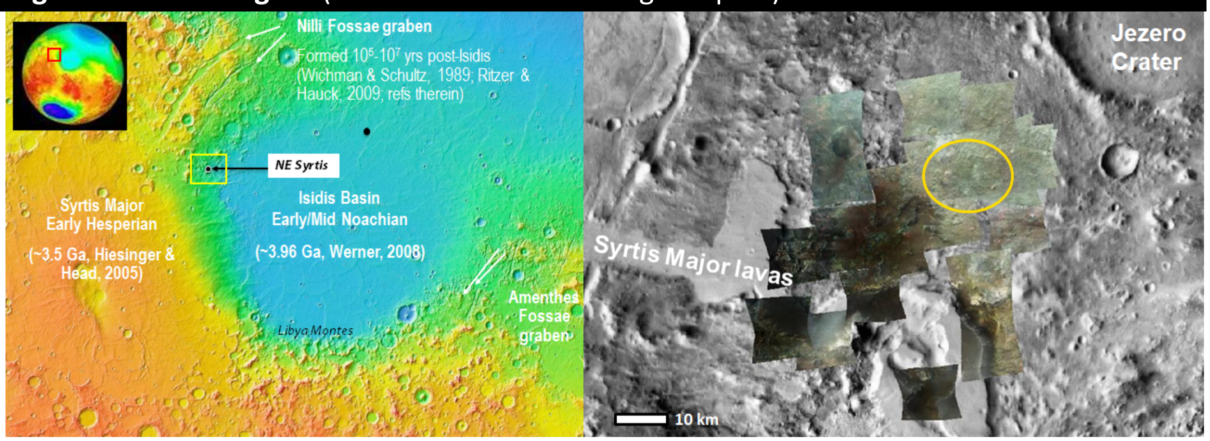
Site Overview:
Ehlmann, B. L., and J. F. Mustard (2012), An in-situ record of major environmental transitions on early Mars at Northeast Syrtis Major, Geophys. Res. Lett., 39, L11202, doi:10.1029/2012GL051594.

Regional context:
Mustard, J. F., et al (2009), Composition, morphology, and stratigraphy of Noachian crust around the Isidis basin, J. Geophys. Res., 114, E00D12, doi:10.1029/2009JE003349.
Ehlmann, B. L., et al. (2009), Identification of hydrated silicate minerals on Mars using MRO-CRISM: Geologic context near Nili Fossae and implications for aqueous alteration, J. Geophys. Res., 114, E00D08.

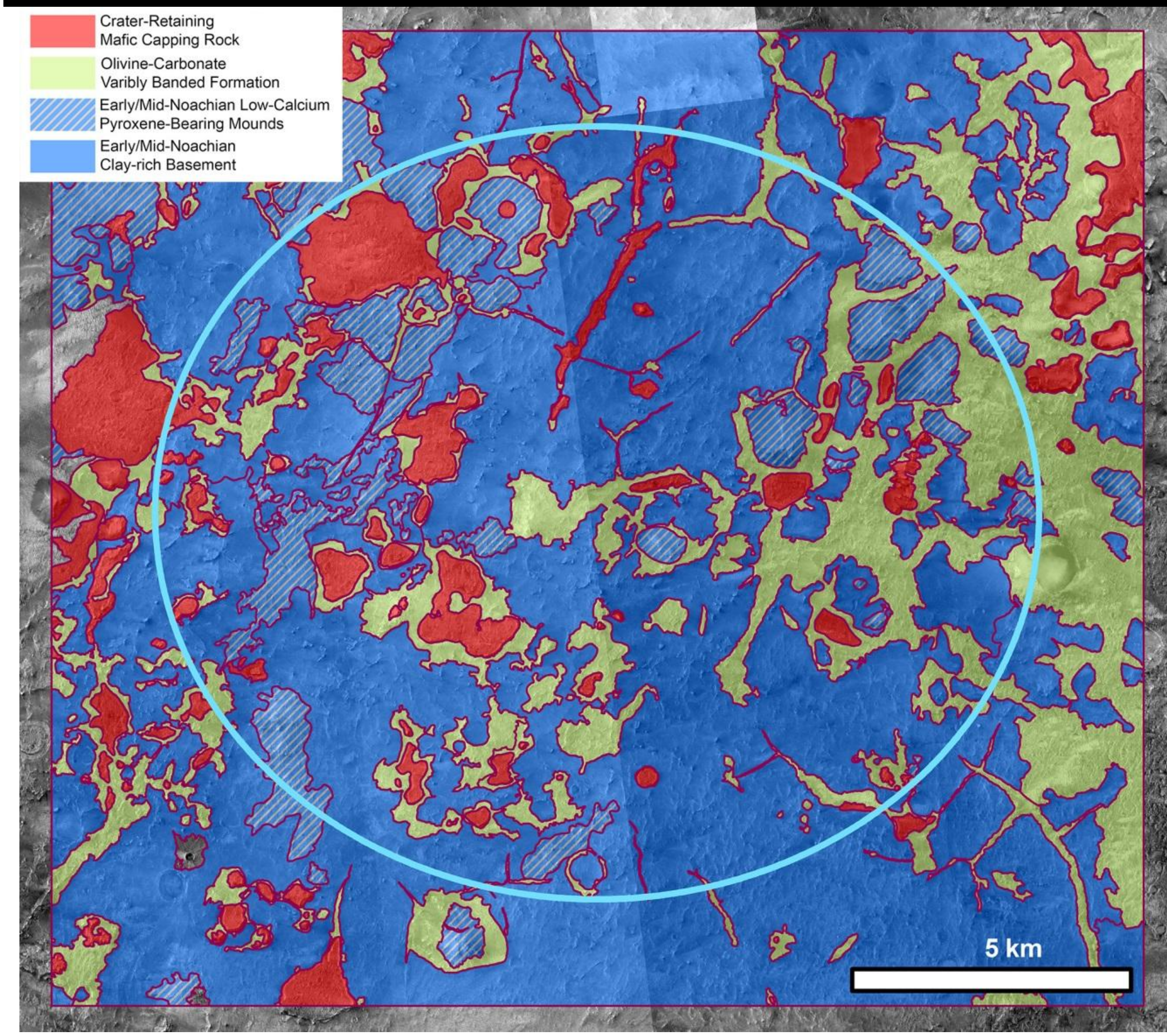
History of volcanism/igneous units:
Ivanov, M. A., and J. W. Head III (2003), Syrtis Major and Isidis Basin contact: Morphological and topographic characteristics of Syrtis Major lava flows and materials of the Vastitas Borealis Formation, J. Geophys. Res., 108(E6), 5063, doi:10.1029/2002JE001994.
Clenet, H., et al. (2013), A systematic mapping procedure based on the Modified Gaussian Model to characterize magmatic units from olivine/pyroxenes mixtures: Application to the Syrtis Major volcanic shield on Mars, J. Geophys. Res. Planets, 118, 1632–1655, doi:10.1002/jgre.20112.

Fluvial activity:
Mangold, N., et al. (2008), Identification of a new outflow channel on Mars in Syrtis Major Planum using HRSC/MEx data, Planet. Space Sci., 56(7), 1030– 1042, doi:10.1016/j.pss.2008.01.011.

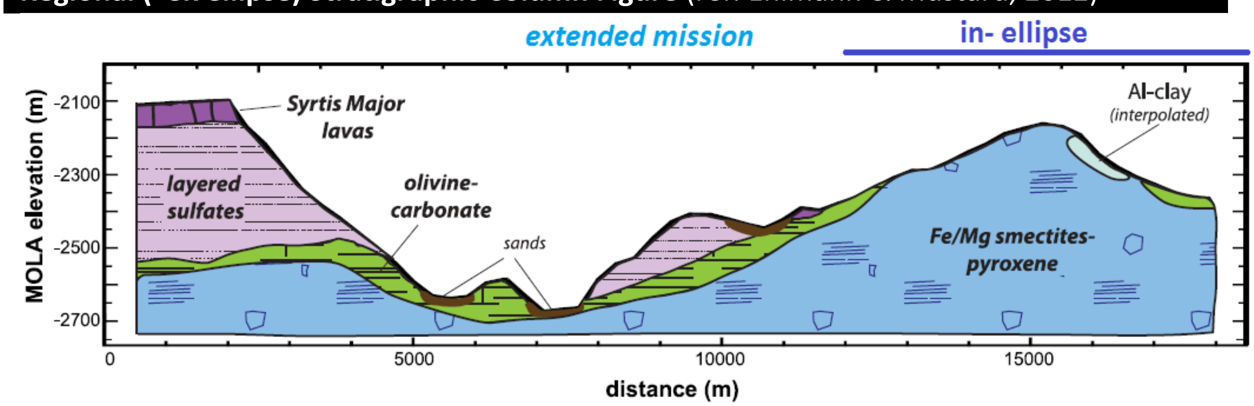
Regional Context Figure (ref: Mustard 2nd landing site pres)



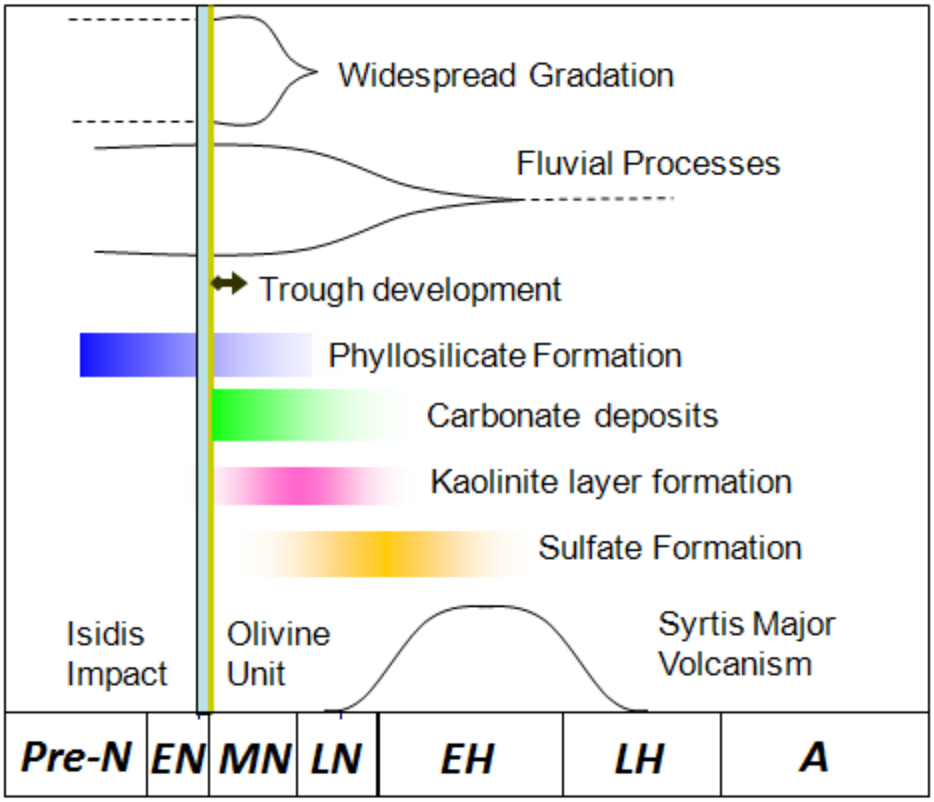
Ellipse ROI Map or Geologic Map Figure (ref: M. Bramble, provided to project)



Regional (~3x ellipse) Stratigraphic Column Figure (ref: Ehlmann & Mustard, 2012)



Inferred Timeline Figure (ref: J. Mustard, 2nd landing site pres.)



Summary of Top 3-5 Units/ROIs

ROI	Aqueous or Igneous?	Environmental settings for biosignature preservation	Aqueous geochemical environments indicated by mineral assemblages
1. Fe/Mg clay-rich basement	aqueous	multiple (subsurface, hydrothermal; sedimentary, fluvial)	Fe/Mg smectites; some sub-units with kaolinite; variable amounts of low-Ca pyroxene from early crust
2. Layered sulfates	igneous/aqueous	hydrothermal; (sedimentary lacustrine?)	Presence of jarosite indicates acidic aqueous conditions.
3. Olivine-carb banded fm	igneous & aqueous	hydrothermal; (sedimentary?)	Olivine-bearing, with variable amts of Mg-carbonate
4. Mafic cap rock	igneous	n/a	Mafic mineral assemblage

Top 3-5 Units/ROIs Detailed Description

Unit/ROI Name:	**Olivine-Carbonate Formation**
Aqueous and/or Igneous?	Both (Aqueous & Igneous)

Description:

A regionally-extensive unit with olivine-basalt variably altered to Mg-rich carbonate; light-toned, polygonally-fractured surface; variable banding is observed.

Interpretation(s):

- Olivine-bearing units formed by impact cumulates (Mustard et al) or lavas (Hamilton & Christiansen; Tornabene)
- Mg-carbonates from near-surface weathering of basaltic products, hydrothermal serpentinization-type reactions, direct hydrothermal precipitation, or shallow aqueous deposition
- Mg-carbonates and phyllosilicates from high-T contact metamorphism (McSween et al.)

In Situ Investigations:

- search for morph/min/org. biosignatures in precipitated carbonates (veins, travertines)
- petrology to determine the environmental conditions of carbonate precipitation: near surface shallow waters vs. hydrothermal springs vs. high-T metamorphism
- search for associated minerals indicating serpentinization vs. weathering-types reactions - morphology, petrology, chem/min to determine origin of the olivine-enriched unit: cumulate vs. lava
- RIMFAX to examine structure of contact with underlying basement units, search for subsurface layering or buried large blocks. Assess any lateral changes in thickness or internal properties.

Returned Sample Analyses:

- search for chemical/isotopic biosignatures
- 12C/13C ratio to constrain paleoatm chemistry, loss rate
- date olivine unit formation to constrain Isidis fm and Martian timescale (post Isidis, pre-Fossae)
- Clumped isotopes for water temperature
- date carbonate formation to determine timing and duration of aqueous activity
- thermometry to determine the conditions of eruption OR cumulate formation

Unit/ROI Name:	**Early/Mid-Noachian Clay-Rich Basement**
Aqueous and/or Igneous?	Aqueous

Description:

A relatively massive basement with interspersed light and dark toned patches and compositionally distinctive subunits. CRISM spectral signatures are observed indicative of Fe/Mg smectites (dominant), low-Ca pyroxene, as well as isolated patches of a kaolin-group mineral (when found, always above the Fe/Mg smectites). Dispersed occurrences of megabreccia are observed in this ROI as well as raised ridges halting at the olivine-rich unit above.

Interpretation(s):

- Mostly Fe/Mg clay sediments deposited during large scale denudation and infilling of the Isidis basin.
- Origin of smectites is poorly constrained - crustal alteration prior to impact, impact-related alteration, pos-impact surface weathering
- Select patches preserve a compositional stratigraphy with Al clays atop Fe/Mg clays, which likely indicates near-surface weathering.
- Included are large breccia blocks, which themselves possess a stratigraphy. These are interpreted

to be pre-existing Early or Pre Noachian crust, sampling what was present prior to Isidis
- The ridges are interpreted to be veins of hydrothermal mineralization
- Igneous materials are low-Ca pyroxene rich and, especially in certain breccia blocks, unaltered to CRISM (no H2O or metal-OH related absorptions)

In Situ Investigations:

- Establish by petrology and small scale geologic context the origin of the clays
- Assess whether the kaolin-bearing materials represent weathering in a clement climate or acid leaching via chemistry of the contact and mineral assemblages
- Search for trapped organics associated with the clay minerals
- RIMFAX to examine internal layering, document detections of subsurface breccias
- Establish the origin of the low-Ca enriched igneous materials and implications for early Noachian magmatic processes

Returned Sample Analyses:

- D/H, oxygen, and other isotopes for atmospheric and water chemistry
- Test for remnant magnetism in unit samples and in pre-Isidis breccia blocks to determine the timing of Martian mag field decline
- Age date materials from the relatively pristine low-Ca pyroxene-bearing subunits
- Study REE patterns in the low-Ca pyroxene bearing materials to understand magmatic reservoirs

Unit/ROI Name:	**Layered Sulfates**
Aqueous and/or Igneous?	Aqueous/Volcanic

Description:

A bright-toned unit with quasi-planar layers that can be contiguous over up to 1 km. Jarosite absorption features are visible within some high-standing bright materials that in some places form a boxwork structure; within the layered deposits are hydrated sulfides with only small jarosite absorptions.

Interpretation(s):

- Presence of jarosite indicates acidic aqueous conditions.
- Boxwork structure with jarosite originated as fluid-filled fractures.
- Possible volcanic/hydrothermal or lacustrine-ground water environment.

In Situ Investigations:

- Perform in-situ petrology to investigate whether the layering is volcanic/lacustrine.
- Perform a stratigraphic cross section through the mesa layers, where it’s possible to drive up and across the mesa layers, to map contacts between sulfates, olivine/carbonates, and basement rock.
- RIMFAX to provide subsurface context for stratigraphy determined from surface investigations; map contacts into the subsurface. Assess continuity and properties of internal layers.

Returned Sample Analyses:

- D/H, oxygen, and other isotopes for atmospheric and water chemistry

Unit/ROI Name:	**Crater-Retaining Mafic Capping Unit**
Aqueous and/or Igneous?	Igneous

Description:

A regionally-extensive unit bearing a crater-preserving dark toned surface composed of meter-scale boulders. This cap sheds boulders and upon erosion exposing a tiered structure where the upper tier is the boulder-rich layer and the lower tier is light toned and polygonally-fractured. This capping unit is spectrally unremarkable with respect to CRISM, but does bear muted mafic signatures.

Interpretation(s):

- Hesperian Syrtis major lava flows, or lithified ash.

In Situ Investigations:

- Assess thickness and layering of the volcanic units.
- Assess through in-situ petrology differences between the upper boulder-shedding and lower tiers.
- RIMFAX to characterize subsurface layering, seek to map boundary between upper and lower tiers if possible to drive high enough. Assess density if possible, to distinguish welded pyroclastics from lava.

Returned Sample Analyses:

- If the capping unit can be reached for sampling, perform dating.

Biosignatures (M2020 Objective B and Objective C + e2e-iSAG Type 1A, 1B samples)

Biosignature Category	Inferred Location at Site	Biosig. Formation & Preservation Potential
Organic materials	Carbonate; sedimentary units in Noach. basement; impact glass, breccia blocks with strat.	Spring-formed carbonates often trap organics; sedimentary clays in basement bind to/are sorted with organics; impact glass may entomb organic materials
Chemical	Carbonate-olivine; Veins within clay-oyx basement, impact glass, breccia blocks with strat.	Zones of mineralization/ chemical alteration gradients may be suggestive

Isotopic	Carbonate unit; Sulfate unit	Carbonate and sulfate isotopic signature can be directly interrogated for atypically light isotopes
Mineralogical	Carbonate; Noachian clay basement, impact glass, breccia blocks with strat.	Spring-formed carbonates often trap organics and may host orientated magnetite; clay sediments may have zones of mineralization related to organic diagenesis
Micro-morphological	Carbonate, Sedimentary units in Noach. clay basement, impact glass	Travertine carbonates commonly preserve textures; Noachian basement seds. may preserve; impact glass may host microtubules
Macro-morphological	Banded carbonate unit; sedimentary clay (basement) and sulfate units (goto)	Mats might be preserved in carbonates or Travertine carbonates commonly preserved; Noachian basement seds. may preserve

Dateable Unit(s) for Cratering Chronology Establishment

Unit Name	Total Area (km^2)	Time Period	Geologic Interpretation and uncertainties	What constraints would the unit provide on crater chronology?
Crater-Retaining Capping Mafic Rock	X.X	LN/EH	(see above) Lithified ash and/or lava with crater age similar to Syrtis Major formation	Crater distribution on unit; measure sample age
Olivine-Carbonate Formation	>1000	EH-LN	(see above) Olivine composition is because emplaced as impact cumulates or lava, post-Isidis but pre-fossae	Tight upper bound on age of Isidis, lower bound on Syrtis lavas, both of which have well-defined global N(D=*)

Key Uncertainties/Unknowns about the Site

- This is the most ancient section under consideration and the precise environmental conditions recorded by the aqueous units are debated by the community and are not resolvable with orbital-scale data
- Biosignature preservation in subsurface habitat is less well-understood than for sedimentary basins.
- The prevalence of clearly sedimentary environments is unknown as multiple hypotheses exist for each of the units. The sulfates almost certainly sedimentary (Quinn et al., 2015, GSA) but the carbonates and the phyllosilicates may have been laid down by first igneous then hydrothermal and weathering processes. An alternative viewpoint is that they are sedimentary, Isidis basin filling deposits. Interestingly, within the basement unit there are some phyllosilicate *breccia blocks* (Early/Pre-Noachian) that do appear to be clearly sedimentary (layered LCP+phyllo; Mustard et al., 2009). This could be an opportunity to sample very, very early sediments (>500 Myr older than Gale/Meridiani sediments).